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Evaluation of Gamma Ray Attenuation for Measuring Soil Bulk Density Part I. Laboratory Investigation

Xiwen Luo
South China Agricultural University

Larry G. Wells
University of Kentucky, larry.wells@uky.edu

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X. Luo, L. G. Wells
MEMBER
ASAE

ABSTRACT

Gamma ray attenuation was evaluated as a means of determining soil bulk density. Experiments were conducted using clay, silt, and sandy loam soils wherein samples were compacted to uniform densities at various moisture contents. We determined the attenuation characteristics of dry soil to be independent of soil texture while being significantly different from that of water. Comparison of gamma density measurements with known soil sample densities indicated that the gamma gauge provided reliable measurement of soil bulk density, provided that the effect of soil moisture on attenuation was accounted for and the manufacturer-prescribed calibration procedure was followed daily. Further, we determined a relationship whereby correction can be made for deviation from the prescribed separation distance between the gamma source and detector. KEYWORDS. Soil, Bulk density, Gamma ray attenuation, Dual probe gauge.

INTRODUCTION

Soil bulk density is an important property germane to many studies, particularly regarding soil compaction. The measurement of soil bulk density has recently been a very active area of research. Techniques have been developed which are suitable for use in both field and laboratory.

The gamma-ray transmission method is one of the most convenient techniques for the nondestructive measurement of soil bulk density and is especially suitable for measurements requiring a high degree of spatial resolution. The dual probe gamma density gauge measures the density of a soil mass situated between a radioactive source and a detector. Its operational principles are well-documented in the literature of soil physics (e.g., van Bavel et al., 1957; Rawitz et al., 1982; Erbach, 1987). Although this device has been widely used, its reliability in accurately measuring soil bulk density has been questioned, particularly with regard to comparison with determinations using volumetric core samples.

Steele et al. (1983) reported that soil bulk density determined using gamma attenuation and manufacturer calibration did not agree with determinations using soil cores over a range of soil types and moisture contents. Erbach (1987) compiled an extensive review of methods for measuring soil bulk density and has indicated a potential error of 0.03-0.05 $Mg{\cdot}m^{-3}$ when using gamma attenuation. Significant issues regarding the appropriate and accurate use of the dual probe gamma density gauge are addressed in this article.

First, in order to use such a gauge, the unattenuated count rate of the source must be determined as well as the attenuation coefficients of dry soil and water. Conflicting determinations of these parameters are found in the literature. In order for the dual probe gauge to provide a significant advantage versus the volumetric core method, these parameters must be determinable without the necessity of calibrating the device for each soil condition or type being measured. In particular, maximum utility would be achieved if a single generic value of the soil attenuation coefficient was applicable to all soils. Also, if the attenuation coefficient of water is significantly different from that of soil, then a simple gravimetric correction for water would be insufficient.

Finally, it is important to maintain a constant horizontal distance or spacing between the source and detector when using the dual-probe density gauge under field conditions. Bertuzzi et al. (1987) reported that a deviation of ± 10 mm from the 200-mm tube separation resulted in a ± 0.15 $Mg{\cdot}m^{-3}$ bias relative to dry bulk density and that the bias increased as the deviation increased. Since assuring constant separation distance in the field is very difficult, it is desirable to investigate the effect of separation distance on the count rate and soil bulk density.

The objectives of this study were to:

- Investigate the effect of soil type on the soil mass attenuation coefficient;
- Investigate the effect of soil moisture on the determination of bulk density using the dual-probe gamma gauge;
- Investigate the effect of the separation distance between the source and detector on the determination of bulk density using the dual-probe gamma gauge; and
- Incorporate those findings in the development of a simple procedure to calculate soil bulk density from the count rate measured with the dual-probe gamma density gauge.

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The authors are Xiwen Luo, Visiting Professor, Agricultural Engineering Dept., South China Agricultural University, China; and Larry G. Wells, Professor, Agricultural Engineering Dept., University of Kentucky, Lexington.

Literature Review

Gamma Attenuation Theory

The theory of gamma ray attenuation has been well-documented by papers such as van Bavel (1959) and Bertuzzi et al. (1987). Monoenergetic gamma ray attenuation by an absorbing soil mass was described as follows:

$$ln(I) = ln(I_0) - x\ \mu_s\ D_{ds} - x\ \mu_w\ D_w\ \theta_v) \qquad (1)$$

where

I = number of gamma photons passing through a soil mass in time t (dimensionless),
I_0 = number of unattenuated gamma photons (passing through air) detected in time t (dimensionless),
x = soil thickness or distance between the source and detector (m),
μ_s = mass attenuation coefficient of dry soil ($m^2 \cdot Mg^{-1}$),
μ_w = mass attenuation coefficient of water ($m^2 \cdot Mg^{-1}$),
D_{ds} = dry bulk density of the soil ($Mg \cdot m^{-3}$),
D_w = bulk density of water ($Mg \cdot m^{-3}$), and
θ_v = volumetric moisture content of soil ($m^3 \cdot m^{-3}$).

Because volumetric soil moisture content can be expressed in terms of gravimetric moisture content:

$$\theta_v = D_{ds}\ \theta_m (D_w)^{-1}$$

where θ_m is the gravimetric moisture content (dry soil basis), equation 1 can be rewritten as:

$$ln(I) = ln(I_0) - x\ \mu_s\ D_{ds} - x\ \mu_w\ D_{ds}\ \theta_m. \qquad (2)$$

Thus, the dry bulk density of soil can be calculated from:

$$D_{ds} = (ln(I_0) - ln(I))\ (x\ \mu_s + x\ \mu_w\ \theta_m)^{-1}. \qquad (3)$$

Mass Attenuation Coefficient of Soil(μ_C)

Soil is composed of several different elements. According to attenuation theory, the mass attenuation coefficient of such a mixture of different elements can be written as:

$$\mu_s = \mu_1\ f_1 + \mu_2\ f_2 + \cdots + \mu_n\ f_n$$

where $\mu_{1...n}$ represents mass attenuation coefficients, and $f_{1...n}$ are the weight fractions of the elements.

Reginato and van Bavel (1964) analyzed nine representative soils of the United States and determined theoretical mass attenuation coefficients at an energy level of 0.662 MeV as listed in Table 1. The soil mass attenuation coefficients varied from 7.72 to 7.80 $m^2 \cdot Mg^{-1}$. Their results indicated that variation of attenuation coefficients among the soils was sufficiently small (<±1%) to justify the use of an average value. By implication, this

TABLE 1. Representative U.S. soils, their chemical composition, and theoretical mass attenuation coefficients at 0.662 MeV*

Soil No.	Soil Type	Great Soil Group	Location	Depth (mm)
1	Carribou loam	Podzol	Houlton, ME	15-40
2	Miami silt loam	Grey-Brown Podzolic	Hancock Co., IN	50-120
3	Norfolk sand	Red & Yellow soils	Mitchell Co., GA	130-240
4	Cecil clay loam	Red & Yellow soils	Greenhill, NC	60-400
5	Marshall silt loam	Prairie soils	Fremont Col., LA	0-100
6	Houston black clay	Prairie soils	Reinhardt, TX	60-140
7	Barnes silt loam	Chernozem	Moody Co., SD	80-230
8	Dark Brown sandy clay	Brown soils	Gillette, WY	90+
9	Mohave loam	Grey Desert soils	Buckeye, AZ	60-140

Element	μ ($M^2 \cdot Mg^{-1}$)	Soil No. 1	2	3	4	5	6	7	8	9
		Composition of oven-dry soil in % by weight								
0	7.75	52.2	50.7	53.3	52.0	50.5	49.8	51.9	50.6	49.6
Si	7.72	37.0	36.2	45.5	23.4	34.0	22.9	33.4	30.7	32.0
Ti		0.5	0.4	0.1	0.8	0.4	0.3	0.4	0.3	0.4
Fe	7.32	0.8	2.2	0.2	6.5	2.2	2.8	3.2	2.8	3.7
Al	7.48	5.1	5.3	0.6	14.1	6.4	5.7	6.2	6.5	7.3
Mn		0.0	0.1	0.0	0.0	0.1	0.1	0.2	0.0	0.1
Ca	7.78	0.1	0.4	0.0	0.0	0.6	10.4	0.8	3.1	1.8
Mg	7.65	0.3	0.4	0.0	0.3	0.6	0.9	0.6	0.8	0.9
K	7.56	1.1	1.8	0.1	1.2	1.8	1.1	1.7	1.8	2.1
Na	7.41	0.9	0.9	0.0	0.3	1.0	0.2	0.9	1.1	1.4
P	7.50	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1
S	7.75	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0
N	7.74	0.1	0.1	0.0	0.0	0.2	0.2	0.1	0.1	0.0
C	7.74	1.4	1.2	0.2	0.3	1.9	4.8	0.8	1.5	0.3
H	15.38	0.5	0.3	0.0	1.1	0.4	0.6	0.5	0.5	0.3
$\mu(m^2 \cdot Mg^{-1})$		7.75	7.73	7.73	7.76	7.74	7.76	7.80	7.74	7.72

* Reprinted with permission from Reginato and van Bavel (1964).

average attenuation coefficient should apply to all soils whose composition falls within the range of constitutive elements which they investigated.

Coppola and Reiniger (1974) analyzed the influence of the chemical composition on the gamma ray attenuation by soils. They concluded that above 0.3 MeV any influence of the chemical compositions on the mass attenuation coefficient of soil was negligible.

Van Bavel et al. (1957) determined the attenuation coefficients of five soil materials at gamma energy 0.661 MeV. They pointed out the variation appeared no greater than about 10% and might, in part, be caused by difference in operating characteristics of the equipment. Van Bavel (1959) also pointed out that the chemical nature of the soil appeared to have no effect upon measured attenuation of gamma rays. Soane and Henshall (1979) also concluded that the count rate of the dual probe gamma gauge was not dependent on soil composition. Rawitz et al. (1982) tested five soils and determined the apparent attenuation coefficients based on measurement in the large containers. These results also indicated very little variation in the mass attenuation coefficient, with variation ranging from 4.95 for clay loam to 5.08 $m^2 \cdot Mg^{-1}$ for a loamy sand.

There seems to be ample experimental evidence to suggest that the difference among theoretical attenuation coefficients determined for various different soils is of no significance in measuring the dry soil bulk density. Therefore, it seems feasible to develop a universal relation between the gamma gauge count rate and dry bulk density which is independent of soil type.

Mass Attenuation Coefficient of Water (μ_w)

Several methods have been utilized to measure the mass attenuation coefficient of water (μ_w). A box filled with water situated between source and detector was used to determine μ_w (Gurr, 1962; de Vries, 1969). Other investigators used trays filled with water (Rawitz et al., 1982) or a combination of glass and water (Reginato and van Bavel, 1964; van Bavel et al., 1985) to determine μ_w. Another approach, which involved placing both source and detector directly into a large container of water, was also used (de Vries, 1969; Rawitz et al., 1982; van Bavel et al., 1985).

Rawitz et al. (1982) reported some effects of system geometry on the mass attenuation coefficient of water. However, van Bavel et al. (1985) concluded that there was no difference in the value of μ_w, whether determined using a tray of water between source and detector or by submerging both within a volume of water of essentially infinite extent. Table 2 lists the mass attenuation coefficient of water as determined by several investigators. Collectively, these results indicated that μ_w is dependent upon the configuration used as well as the distance separating source and detector.

Absorber Thickness (x)

Because the source and detector are usually placed within two parallel aluminum tubes, various procedures are used to calculate absorber thickness, x, shown in equation 1. Van Bavel (1959) defined x as the average of the center-to-center distance and the separation distance between the tubes. Other authors only considered the separation between tubes (Reginato and van Bavel, 1964) or the center-to-center distance (van Bavel et al., 1985). Since x is defined as the absorber thickness, we chose the separation distance between tubes as its measure.

It is difficult to maintain uniform, accurate separation between tubes under field conditions. Van Bavel et al. (1957) investigated the effect of distance on count rate in five different, homogeneous soil masses. They determined the product of count rate and x^2 to be proportional to log x. Such a relationship could thus be used to "correct" count rate based upon a particular value of x.

TABLE 2. Mass attenuation coefficient of water(μ_w)

Source	Method	μ_w ($m^2 \cdot Mv^{-1}$)	Separation Distance
Gurr, 1962	Box filled with water	8.56	150.3 mm
Reginato et al., 1964	Glass-water system	7.48	303 mm, w-w*
de Vries, 1969	Box-filled with water,		
	without collimation	7.19	266 mm
	with collimation	8.38	186 mm
Reginato et al., 1971	Tubes flooded with water	5.00	200 mm
Reginato, 1974	Water in plastic bag	4.80	100 mm, w-w
Rawitz et al., 1982	Water in large plastic	5.86	306 mm, c-c†
	Water in swimming pool	5.63	306 mm, c-c
van Bavel et al., 1985	Glass-water system	8.62	254 mm, w-w
		7.11	254 mm, w-w
		6.94	254 mm, w-w
	Large container of water	7.11	254 mm, w-w
Bertuzzi et al., 1987	Large container of water	8.57	

* The distance between wall of the source tube and wall of the detector tube.

† The distance from the center of the source tube to the center of the detector tube.

Unattenuated Count Rate (I_0)

The unattenuated count rate I_0 is a measure of the radiation intensity of the source. Since this rate is too high for accurate counting, it is usually extrapolated from the rates measured through multiple glass or aluminum plates placed in a rectangular holder situated between the source and detector. Reginato et al. (1971) determined I_0 as the count rate through air only. Rawitz et al. (1982) reported I_0 to be dependent on the configuration utilized in measurements, and indicated that the value of I_0 may be specific to an individual device. However it is determined, the attenuated rate is a necessary parameter for use of equation 3.

Experimental Procedures

Equipment

The equipment used in this study was a Troxler model 2376 dual probe density gauge. It consisted of a 5.8 mCi source of Cs 137 emitting photons with a peak gamma energy of 0.662 MeV, a sodium iodide crystal scintillation detector, a parallel access hole guide, a calibration stand, and a portable scaler rate meter with a pulse height discriminator unit (model 2651). The calibration stand consists of two parallel 51-mm (2-in.) diameter tubes (0.8 mm wall thickness) separated by 254-mm (10-in.) center-to-center. Four blocks of homogeneous materials with differing densities were mounted between the tubes: polyethylene, magnesium, limestone, and aluminum.

TABLE 3. Particle size distribution of experimental soils

Soil	Percent Clay (≤ 2 μm)	Percent Silt (2 μm < dia. < 53 μm)	Percent Sand (≥ 53 μm)
Silt loam	20.3	54.8	24.9
Clay loam	36.4	40.3	23.3
Sandy loam	15.2	21.4	63.4

Experimental Soils

The soils used in this investigation were classified as silt loam, clay loam, and sandy loam according to USDA textural triangle procedure. They were taken from the field and were hand-screened to remove roots, gravel, and other foreign matter. Table 3 shows the particle size distribution of these soils.

Calibration Procedures

A plexiglass calibration holder was constructed for use in determining the unattenuated count rate and the attenuation coefficients of soil and water following a procedure similar to that described by Rawitz et al. (1982). The holder was 254 mm (10 in.) long, 76 mm (3 in.) wide, and 51 mm (2 in.) deep so that it could be placed between the parallel tubes of the calibration stand.

Aluminum plates, approximately 6.4 mm (0.25 in.) thick, were placed in the calibration holder and count rates were recorded using 1 to 20 plates as well as the four blocks of homogeneous materials. Five one-minute counts were recorded for each configuration. The mean count rate for each density was used to define the regression relationship:

$$ln(I) = ln(I_o) + C_1 D_1 \qquad (4)$$

where

I = count rate,
I_o = unattenuated count rate,
C_1 = constant, and
D_1 = density of the *ith* plate or block.

By letting $D_1 = 0$ in equation 4, we can determine the unattenuated count rate (I_o).

The three previously described soils were used to measure the soil mass attenuation coefficient (μ_s). After oven drying for 24 hours at 105° C, samples of each soil were uniformly packed into the calibration box and corresponding count rates determined. Two levels of compaction were used and 10 one-minute counts were recorded for each sample. If we let $\theta_m = 0$, equation 3 yields:

$$\mu_s = \frac{ln(I_o) - ln(I)}{x\, D_{ds}} \qquad (5)$$

The mass attenuation coefficient of soil can be determined since I_o, x , and D_{ds} are assumed known.

Both distilled water and tap water were placed in the calibration holder box in order to determine the attenuation coefficient of water (μ_w). To investigate the effect of the system geometry, the source and detector were also directly placed in a large mass of water 1420 mm (55.9 in.) long, 520 mm (20.5 in.) wide, and 520 mm (20.5 in.) deep. If $x\, \mu_s\, D_{ds} = 0$, then equation 1 reduces to:

$$\mu_w = \frac{ln(I_o) - ln(I)}{x}. \qquad (6)$$

Thus, μ_w can be determined by measuring I, when x and I_o are known.

Bulk Density Measurement Procedures

The silt loam, clay loam, and sandy loam soils were also used to investigate the calibration and measurement procedures associated with the dual probe density gauge. Soil samples were prepared from the same three soil types and placed in a wooden box 508 mm (20 in.) long, 178 mm (7 in.) wide, and 305 mm (12 in.) high. Four levels of moisture content were achieved by adding a desired amount of water to a given mass of soil and allowing 24 h in order for moisture content to reach equilibrium or become uniform. Soil was then placed in the wooden box by layers and compacted using a drop hammer.

Six levels of compaction were achieved for each moisture content by varying the number of hammer blows applied to the soil. The average density of each soil sample was calculated from known sample weight and volume. After placing soil in the box at a uniform bulk density and moisture content, parallel access tubes were installed at a spacing of 254 mm using the manufacturers hole template. Soil samples were 203-254 mm (8-10 in.) high and the radioactive source and detector were placed at the center of each sample.

Whenever the radioactive source and detector were transferred from a low density medium (air) to a higher density medium (soil), the count rate decreased in an exponential fashion until it reached a steady level. Thus, each time the source and detector were placed within access tubes, sufficient time was allowed for the count rate to stabilize. After a stable count rate was indicated, five two-minute readings were recorded. The highest and lowest count rate were rejected and the average of the three median count rates was used as the count rate I in equation 1.

To investigate the effect of spacing between access tubes, another wooden box, 457 mm (18 in.) square and 305 mm (12 in.) high was constructed. The spacing between access tubes was varied from 203 (8 in.) to 305 mm (12 in.) at increments of 127 mm (0.5 in.). The required number of holes to achieve the spacings were drilled in the same soil sample. Thus, the soil parameters were considered invariant.

Calculation of Soil Bulk Density

If the unattenuated count rate (I_o), the mass attenuation coefficients of soil and water (μ_s and μ_w) and the gravimetric moisture content (θ_m) are known, then the dry bulk density of soil can be calculated from equation 3. However, manufacturers of dual probe gamma density gauges generally provide an alternative procedure based on the determination of regression coefficients via calibration using homogeneous materials of known density. We used the calibration stand previously described, which contains four homogeneous materials, and developed the following regression relationship:

$$ln(CR_j) = a + b\ D_j \qquad (7)$$

where

CR_j = count ratio = $I_j \div I_r$,
I_j = count rate within a material of known density,
I_r = count rate of a reference standard material (magnesium),
a, b = regression coefficients, and
D_j = bulk density of material j.

If we define $A = e^a$ and $B = -b$, then the composite bulk density (D_{ws}) of soil (including water), can be calculated from:

$$D_{ws} = \frac{\left(ln\left(\frac{A}{CR}\right)\right)}{B} \qquad (8)$$

where

CR = count ratio = $I \div I_r$,
I = count rate within the soil, and
I_r = count rate within the reference standard (magnesium).

Because D_{ws} is the bulk density of the mixture of soil and water, we refer to it as wet bulk density.

If the mass attenuation coefficient of water and soil were equal, we would calculate the dry bulk density of soil as follows:

$$D'_{ds} = \frac{D_{ws}}{(1 + \theta_m)} \qquad (9)$$

where θ_m represents the gravimetric moisture content.

Similarly, by substituting μ_s for μ_w in equation 3, we would also obtain:

$$D'_{ds} = \frac{ln(I_o) - ln(I)}{x\ \mu_s(1 + \theta_m)}. \qquad (10)$$

As stated previously, however, a significant difference between the mass attenuation coefficients of soil and water has been documented by several investigators. Thus, $\mu_w \neq \mu_s$ and if we assume:

$$\mu_w = C_2\mu_s \qquad (11)$$

then, by combining equation 11 and equation 3, we obtain:

$$D_{ds} = \frac{ln(I_o) - ln(I)}{x\ \mu_s(1 + C_2\,\theta_m)} \qquad (12)$$

where, theoretically, D_{ds} is the best possible estimate of true dry soil bulk density. Comparing equation 12 and equation 10, we can get:

$$\frac{D_{ds}}{D'_{ds}} = \frac{1 + \theta_m}{1 + C_2\,\theta_m} \qquad (13)$$

which combined with equation 9 gives:

$$D_{ds} = \frac{D_{ws}}{1 + C_2\,\theta_m}. \qquad (14)$$

Steele et al. (1983) compared soil bulk density determined by a dual probe gamma attenuation gauge with that volumetric cores using several soil types. Measurements were taken from large soil bins at several depths, with soils ranging from clay to sand in textural classification. They determined that it was necessary to develop an empirical calibration equation for each soil condition and depth in order to obtain acceptable agreement between the two methods in determining wet bulk density. Thus, they determined a quadratic regression equation expressing wet bulk density (D_{ws}) as a function of count ratio (CR) for each soil condition-depth.

We chose a somewhat simpler regression model to determine if empirical calibration of the gamma gauge versus volumetric cores for each soil type would significantly improve agreement between the two methods. The arbitrary form chosen was:

$$D_{ds} = (C_3 + C_4\,\theta_m)D_{ws} \qquad (15)$$

where D_{ws} was determined using the gamma gauge, θ_m was measured gravimetrically, D_{ds} was determined using volumetric cores, and C_3 and C_4 are best-fit regression coefficients.

It is well established that count ratio (CR) is inversely proportional to the square of the distance between gamma source and detector. If kx^2 is substituted for CR in equation 8, then it follows that bulk density is a linear function of ln x. Because ln x is approximately linear for (200 mm ≤x≤300 mm), the following equation can be used to accurately correct for deviations in source/detector spacing:

$$D_{ds} - D^*_{ds} = C_5 + C_6(x_s - x^*_s) \qquad (16)$$

where

D_{ds} = apparent dry soil bulk density ($Mg{\cdot}m^{-3}$),
D^*_{ds} = dry bulk density computed at the correct source/detector spacing ($Mg{\cdot}m^{-3}$),
x_s = source/detector spacing corresponding to D_{ds} (mm),
x^*_s = desirable source/detector spacing = 254 mm (10 in.), and
C_5, C_6 = regression coefficients.

Various approaches may thus be followed in using the dual probe gamma density gauge to determine dry soil bulk density. For this study, the following procedures were evaluated:

1. The general relationship describing dry soil bulk density as a function of gamma ray count rate (eq. 3) was followed, and the parameters I_o, μ_s, and μ_w were experimentally determined. This method entails the most rigorous gauge calibration and is designated as the theoretical calibration (TC) method.
2. The manufacturer's recommendation for gauge calibration was followed by using the calibration stand and determining the coefficients A and B of equation 8 by regression. Equation 14 was followed

to convert from wet (eq. 8) to dry soil bulk density. The parameter C_2 was assumed constant and independent of soil type. This method was designated as the modified manufacturer (MM) calibration method.

3. The final method is similar to the MM except that equation 15 was used instead of equation 14 to compute dry bulk density from wet bulk density as determined using equation 8. The regression coefficients C_3 and C_4 are soil-specific and, thus, this method is designated as the regression calibration (RC) method.

The following section presents the results of experimental calibration procedures as well as an evaluation of the various methods of determining dry soil bulk density.

Results and Discussion

The results of the procedure followed to determine the unattenuated count rate, I_0, are presented in Table 4. The high value of R^2 indicates that the data fit equation 4 very well and that I_o = 178,937 cpm should be a very accurate estimate.

The experimentally determined values of mass attenuation coefficient of the soils investigated and that of water are given in Tables 5 and 6, respectively. Values of μ_w were relatively independent of the presence of dissolved minerals or the extent of water volume. These results agree with those reported by van Bavel et al. (1985). Although Table 2 indicates substantial disagreement between some investigators concerning the value of μ_w, we conclude that the results in Table 6 are reasonable; thus, we determined $\mu_w = 6.28\ m^2 \cdot Mg^{-1}$. Choosing the average value of μ_s from Table 5, the ratio $\mu_s/\mu_w = 5.63/6.28 = 0.8965$. This agrees quite well with the ratio determined by taking the mean of the theoretical values of μ_s for nine representative U.S. soils and the value of μ_w reported by Reginato and van Bavel (1964) (see Table 1) i.e., $\mu_s/\mu_w = 7.75/8.62 = 0.8991$.

Analysis of variance indicated no significant difference (5% level) between means associated with the method of determining bulk density, volumetric core versus gamma gauge calibration, for the sandy loam soil or the composite data of all three soil types. However, significant difference was indicated at the 5% level for both clay and silt loam soils. In figures 1-3, the regression calibration method (RC) appears to produce the best agreement in all three soil types. In the silt loam and clay loam soils, the theoretical (TC) and the modified manufacturer's (MM) calibration tended to underestimate packing bulk density by approximately 5%, whereas the RC method overestimated by approximately 0.5%. The accuracy of the RC method was also best in the sandy loam soil (+1.4%), however, the MM and TC errors were only −3.4 and −1.9%, respectively.

Linear regression was used to quantify the relative accuracy of the various gamma gauge calibration methods which are illustrated in figures 1-3. The various regression parameters are presented in Table 7. In all but one case, the estimated or computed slope was less than 1, indicating a tendency for the gamma gauge to underpredict core densities which increases with increasing bulk density. Positive intercepts in all cases would indicate a compensating underprediction at lower density, however, this occurred only for the regression calibration method within the range of bulk density investigated. The regression lines show a clear tendency for the regression calibration to predict higher density than the other methods. There was very little difference between the manufacturers and theoretical calibration methods, especially for the silt and clay soil types.

Duncan's new multiple range test (SAS, 1986) was used to further test for differences between measurement methods and calibration procedures and the results are presented in Table 8. No method of calibration produced mean values which were significantly different from known packing density in a given soil type at the 5% level of significance. Only in the case of the silt loam soil were

TABLE 4. Gamma count rate vs. density using aluminum plates in a calibration box and the manufacturer's calibration stand to determine unattenuated count rate (I_o)

No. of Plates	Count Rates (cpm)	Density $Mg \cdot m^{-3}$	Regression Results
1	141,759	0.0929	
2	132,799	0.1679	
3	121,897	0.0279	
4	112,241	0.3079	
5	102,761	0.3779	
6	93,231	0.4479	
7	85,722	0.5180	I_o = 178,937 cpm
8	78,647	0.5880	
9	70,481	0.6580	
10	64,518	0.7628	C_1 = 0.6299
11	58,689	0.7980	
12	53,674	0.8680	
13	48,427	0.9380	R^2 = 0.9980
14	43,213	1.0080	
15	28,835	1.0780	
16	35,269	1.1480	
17	32,060	1.2180	
18	29,286	1.2880	
19	26,266	1.3580	
20	23,907	1.4281	
Manufacturer's Calibration Stand			
Polyethylene	38,058	1.055	
Magnesium	13,326	1.769	
Limestone	6,918	2.206	
Aluminum	3,405	2.632	

TABLE 5. Mass attenuation coefficient of soil (μ_s)* ($m^2 \cdot mg^{-1}$)

Silt Soil	Clay Soil	Sandy Soil	Average Value
5.72	5.56	5.64	5.63

* Calculated from equation 5 with I_o = 178.937 and x - 265 mm.

TABLE 6. Mass attenuation coefficient of water (μ_w)*

Pure Water in Small Box	Tap Water in Small Box	Large Body of Tap Water
6.34	6.27	6.28

* Calculated from equation 5 with I_o = 178.937 and x = 254 mm.

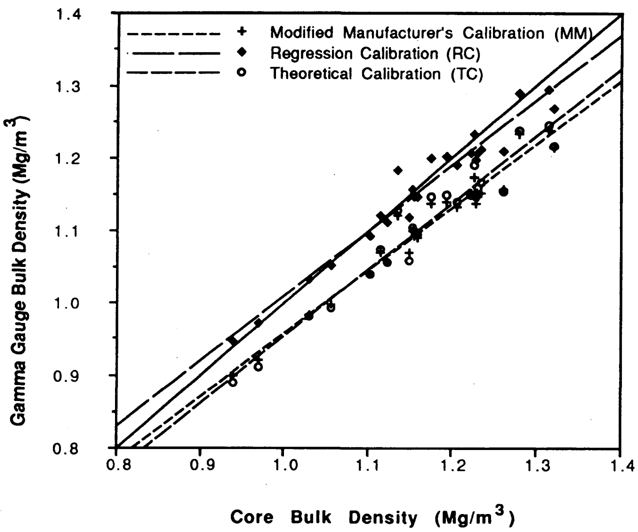

Figure 1–Gamma gauge bulk density via three calibration methods vs. known sample bulk density (silt loam soil).

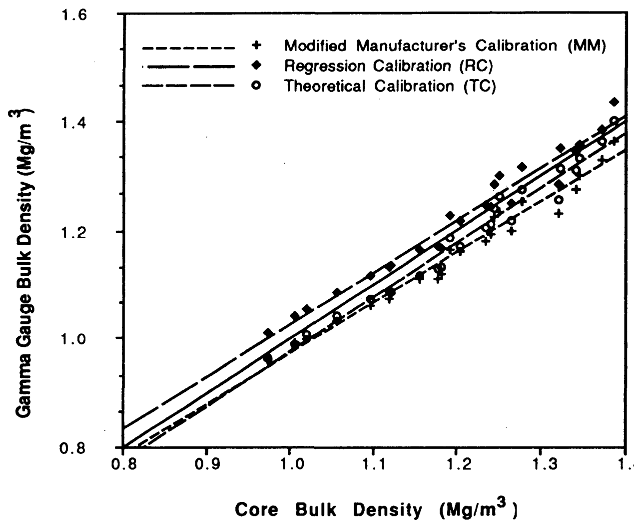

Figure 3–Gamma gauge bulk density via three calibration methods vs. known sample bulk density (sandy loam soil).

any of the calibration methods statistically different, and in this case the regression method (RC) produces density values significantly greater than the modified manufacturer's (MM) method. It should be noted that when the composite results of data from all three soil types were considered, only the modified manufacturer's method (MM) produced density values significantly different from the packing density. Also, the determination of $C_2 = \mu_w/\mu_s = 1.115$ ($\neq 1.0$) contributed to the tendency of the modified manufacturer's calibration (MM) to underpredict dry bulk density. However, the actual percentage error was relatively small ($\leq 3.5\%$), and it is presumed that the ability to normalize measured attenuation rates by periodically determining attenuation in a reference material of known density would result in greater reliability and utility for extended use of a gauge over time. Overall, we concluded that soil bulk density as determined by the gamma gauge is not significantly different from "known" packing density and that use of the manufacturer's calibration procedure (eq. 8) is adequate when modified by use of equation 14.

We cannot explain the apparent consistent underprediction of soil bulk density resulting from both the MM and TC calibration methods. The results of this and a companion study (Wells and Luo, 1992) indicated that the tendency occurred over both field and laboratory measurements involving five distinct soils. Insofar as this study is concerned, accuracy of gamma density measurements would be improved by increasing them by 3-5%.

Figures 4-6 show that there was apparently no effect of soil moisture content upon the relative accuracy of the various calibration methods in any of the soil types tested. This was confirmed by Pearson correlation coefficients (relating moisture content to the difference between gamma and gravimetrically determined densities) corresponding to the MM, RC, and TC calibration methods of 0.01937, 0.07638, and 0.04840, respectively (SAS, 1986). Also, the level of soil bulk density had no apparent

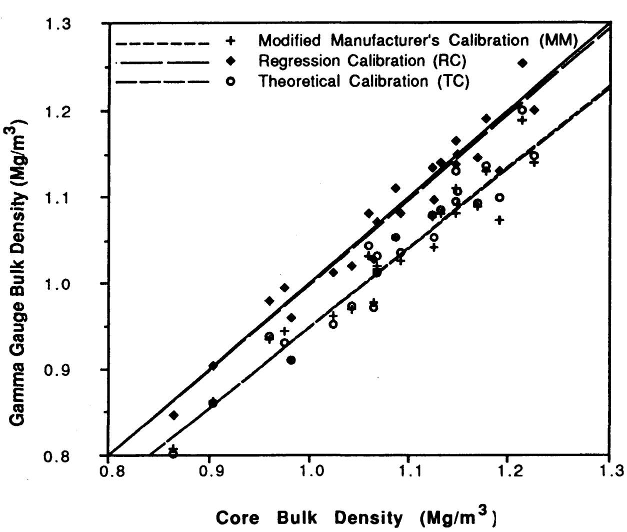

Figure 2–Gamma gauge bulk density via three calibration methods vs. known sample bulk density (clay loam soil).

TABLE 7. Linear regression parameter of core vs. gamma gauge soil bulk densities

	Silt Loam		
	Manufacturer's Calibration	Theoretical Calibration	Regression Calibration
Slope	0.871	0.919	0.897
Intercept	0.087	0.034	0.112
R^2	0.959	0.948	0.951
	Clay Loam		
	Manufacturer's Calibration	Theoretical Calibration	Regression Calibration
Slope	0.926	0.926	0.986
Intercept	0.220	0.220	0.011
R^2	0.946	0.830	0.943
	Sandy Loam		
	Manufacturer's Calibration	Theoretical Calibration	Regression Calibration
Slope	0.927	1.008	0.957
Intercept	0.047	0.033	0.068
R^2	0.974	0.973	0.967

TABLE 8. Duncan's new multiple range test of soil bulk density ($Mg \cdot m^{-3}$) associated with gamma gauge calibration methods

Soil*	Packing Density	Modified Manufacturer's Calibration	Regression Calibration	Theoretical Calibration
Clay Loam	1.078 a	1.025 a	1.109 a	1.029 a
Silt Loam	1.166 bc	1.103 b	1.176 c	1.118 bc
Sandy Loam	1.205 d	1.163 d	1.225 d	1.184 d
Composite	1.150 ab	1.097 c	1.170 ab	1.110 bc

* Within a soil type, means designated by the same letter are not different at the 5% level of significance.

effect on the error associated with the various calibration procedures. The RC procedure resulted in a slight tendency to overpredict bulk density by an amount independent of density level. Also, the TC and MM calibration methods tended to underpredict bulk density by a constant amount (5%) over the density range studied ($0.9 \le D_{ds} \le 1.4$ $Mg \cdot m^{-3}$). Perhaps this tendency to underpredict arises from the additional passage of gamma photons through continuous or nearly continuous lateral soil pores. Such an hypothesis would be supported by the relatively smaller underprediction in the sandy loam soil, where packing density is higher due to a wider range of soil particle size.

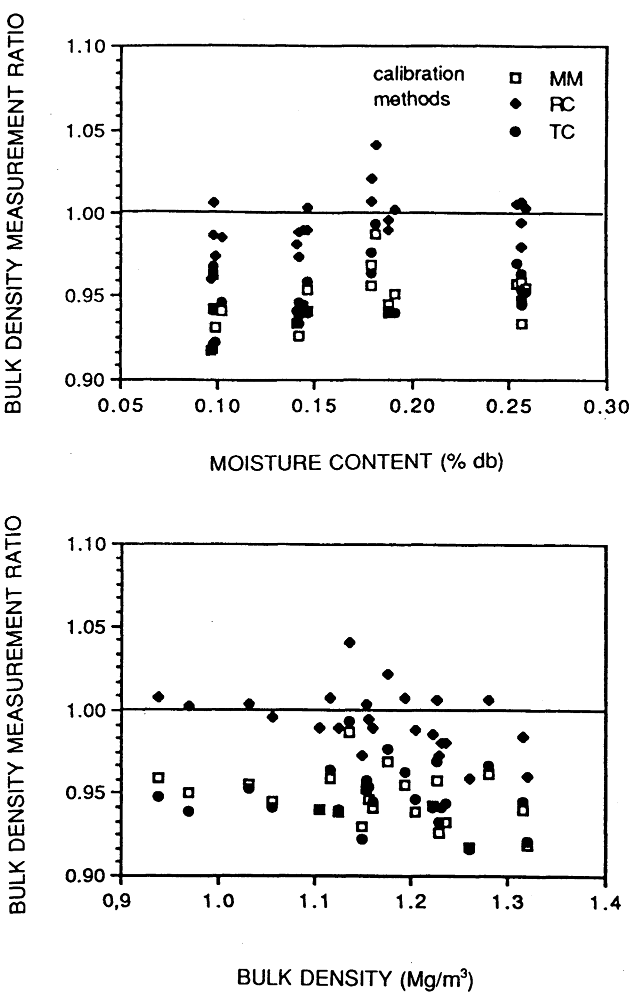

Figure 4–Bulk density measurement ratio (gamma gauge density/ sample density) vs. moisture content using three calibration methods (silt loam soil).

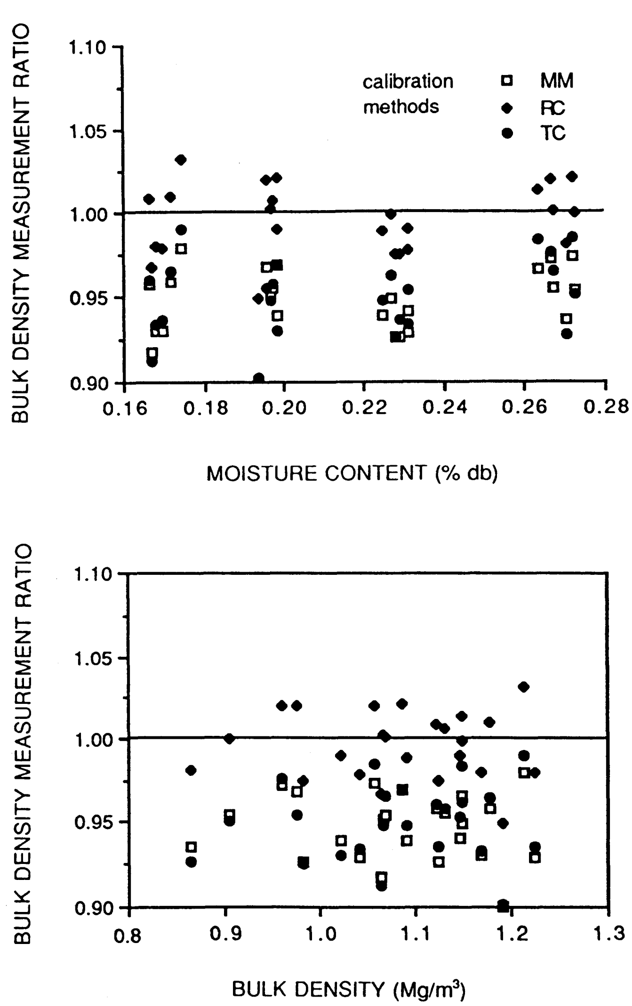

Figure 5–Bulk density measurement ratio (gamma gauge density/ sample density) vs. moisture content using three calibration methods (clay loam soil).

Although the regression calibration procedure (RC) yielded superior agreement with known density for all soil types, this is of little utility in that the necessity of calibrating the gauge for each soil type being tested would seriously limit its use. Thus, there remains the question whether the other calibration methods provide comparable accuracy in field applications. This is addressed in Part II of this study.

Figure 7 shows the extreme effect of deviation from 254 mm (10 in.) spacing between the gamma source and detector for a laboratory silt loam soil. Clearly, use of a gamma gauge to determine valid soil bulk density requires: 1) accurately establishing the correct spacing; or 2) compensating for a known deviation in spacing. In figure 7 the deviation from true bulk density ($D_{ds} - D^*_{ds}$) was approximately a linear function of deviation from the correct source/detector spacing ($x_s - x^*_s$). When equation 16 was used to describe observed variation of measured bulk density to deviation of source/detector spacing, the correlation coefficient (R^2) for these measurements was 0.997. Figure 7 shows the application of equation 16 to correct the erroneous densities inferred when spacing was not 254 mm (10 in.).

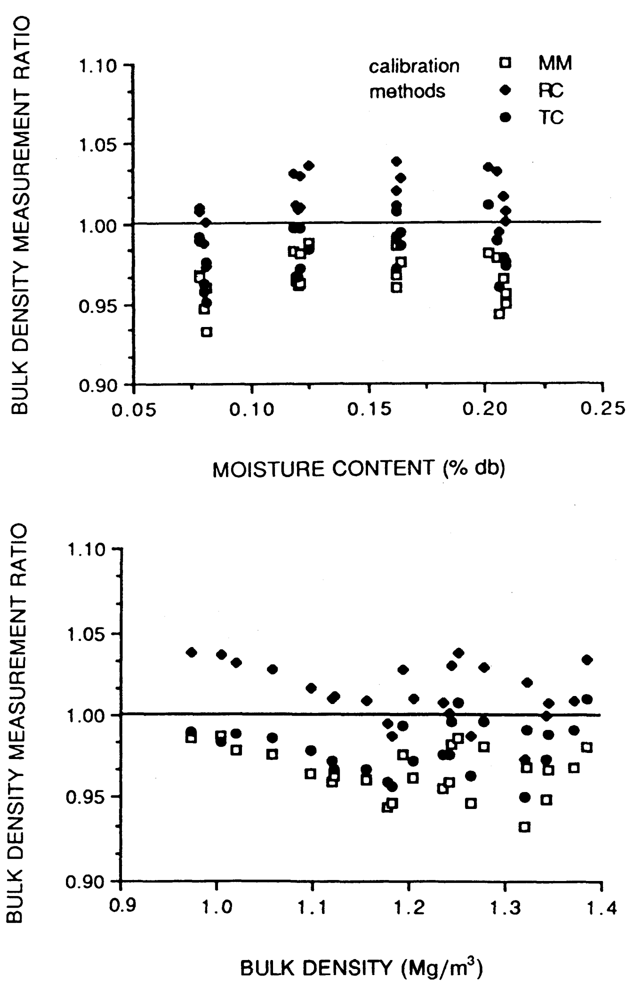

Figure 6–Bulk density measurement ratio (gamma gauge density/sample density) vs. moisture content using three calibration methods (sandy loam soil).

Clearly, then, we can correct or compensate for inaccurate separation of source and detector provided that the spacing is measured and recorded when gamma counts are being recorded. This should be standard practice, along with the determination of soil moisture content, whenever a

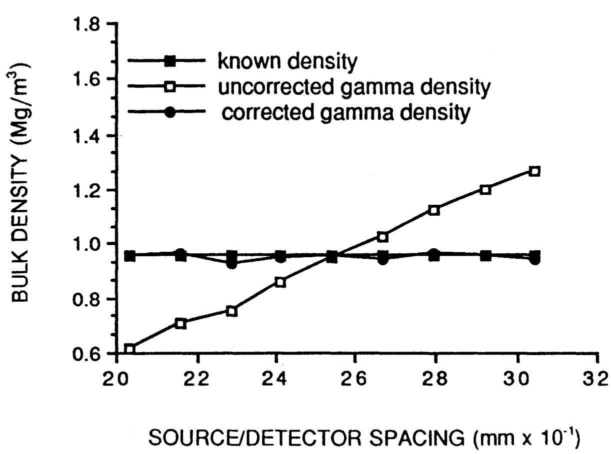

Figure 7–Comparison of corrected and uncorrected gamma gauge density vs. known density (silt loam soil).

gamma density gauge is used. If these measures are taken and the gauge is calibrated regularly, then reliable and meaningful measurement of in situ field soil bulk density should result.

Conclusions

Based on the results reported herein, the following conclusions are drawn:

1. The effect of soil type on gamma ray attenuation at 0.662 MeV is negligible.
2. The attenuation coefficient of water is significantly different from that of soil. The measured ratio of μ_w/μ_s reported in this study is consistent with other investigations.
3. There was no significant difference (5% level) between any of the gamma gauge calibration methods used (modified manufacturer's, theoretical or regression) and the gravimetrically determined soil bulk densities for any of the soil types investigated. However, the composite results of all three soil types indicated a significant (5% level) difference only when the modified manufacturer's calibration procedure was used. In general, the manufacturer's calibration procedure underpredicted gravimetric bulk densities by approximately 3.5%.
4. Within the ranges evaluated in this study, soil moisture content and soil bulk density level had no effect upon the accuracy of the gamma density gauge.
5. A linear relationship exists between deviation from correct source/detector spacing and the difference between apparent and true soil bulk density. This relationship can thus be used to correct for the occurrence of spacing deviation in field measurements.

We generally conclude that the gamma gauge is an effective and reliable method for determining soil bulk density.

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